SEMI - FLEXIBLE SELF VARYING CAMBER RUDDER

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Thesis
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15 May 1950

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled "Semi-flexible Self Varying Camber Rudder."

Respectfully,

SEMI-FLEXIBLE SELF VARYING CAMBER RUDDER

by

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NOMENCLATURE

C_L - Lift coefficient (dimensionless)

C_D - Drag coefficient (")

F_L - Lift force, lbs.

F_D - Drag force, lbs.

V - Water velocity, ft/sec.

ρ - Water density

S - Model rudder area (projected)

I. SUMMARY

The object of the work undertaken in preparation of this thesis is the comparison of Lift and Drag Coefficients of an all metal rudder (parent) with those of a family (five) of dimensionally equal rudders which have been modified by cutting away varying percentages of the trailing edge of the parent rudder and replacing the cut away portion with rubber. In order to maintain dimensional equality, six bronze rudders were cast to the same mold, and five were modified as described above. Basic rudder characteristics are: chord - six inches, aspect ratio - one, thickness ratio - 0.19, balance - 20.8%.

Test runs were made in the M.I.T. propeller tunnel at a constant water velocity of 9 feet per second. Lift and drag forces were measured from zero to thirty five degrees angle of attack by means of strain gages mounted in the lower end of a rudder dynamometer. These forces were then converted to dimensionless lift and drag coefficients by dividing the force obtained by the product of: 1/2(water density)x(rudder area) x(water velocity)^2.

The experimental work accomplished shows that, with respect to the all metal rudder (parent), the use of a rubber trailing portion up to about 25% rubber has the effect of increasing the Lift Coefficient, the maximum increase occurring with about 12% rubber and being of the order of 2.8% increase at 30° rudder angle; 7.1% increase at 20°; 10.7% at 10°; and about 25% increase at 5° rudder. Similarly for the Drag Coefficient, a slight increase develops with increase in percentage of rubber up to about

SUMMARY

25% rubber, beyond which an increase in percentage of rubber tends to cause the Drag Coefficient to decrease. With 12% rubber the increase in the Drag Coefficient is as follows: 5.5% increase at 30° rudder angle: 6.5% increase at 20°; 13.8% increase at 10°; and 13.3% at 5° rudder angle.

If the ratio of the Lift Coefficient to the Drag Coefficient is to be used as a criterion in judging the relative performance of the rudders, it is noted that the 40% and 50% rubber rudders have considerably higher ratios than the parent rudder.

From the results of the experimental work accomplished, it is concluded that the lift Coefficient is increased, with respect to the parent (all metal rudder), with the use of a rubber trailing edge up to about 25% rubber. Beyond 25% rubber the Lift Coefficient decreases. The Drag Coefficient increases with the addition of rubber up to about 25% rubber and thereafter decreases with the use of more rubber. From a careful study of the results obtained and close observation of the rudders in the tunnel it is concluded that the rubber used was too stiff, in that it did not bend as much as was expected when subjected to the action of the water force.

In view of the results obtained from the experimental work accomplished to date with the rubber-tipped rudders, it is recommended that further experimental work be carried out with them along the following lines:

a) Utilizing rudders with rubber of varying degrees of stiffness.

b) Conducting a close search of the area within which the percentage of rubber varies from 5% to 15%.

c) Performing experiments with all rubber rudders in which the forward part of the rudder is internally stiffened so as to be inflexible for all practical purposes, but a smooth continuous surface is presented to the flow of water around the rudder.

d) Investigating the effects of a ship's hull and propeller upon the behavior of rubber tipped rudders.

II. INTRODUCTION

The problem approached in the development of this thesis is the one of providing, for vessels moving through a fluid medium, a control surface which will permit adequate directional control with a minimum of undesirable effects; in the case of a rudder, this means providing maximum lift with minimum drag. The literature cited in Appendix E gives evidence of the extensive research effort directed towards this end.

The use of a rubber tipped rudder, it was thought, would permit the trailing portion of the rudder to fair into the stream of water passing it, to a certain degree, with the result that a small amount of camber would be placed on the rudder. The placement of such camber would be entirely independent of outside mechanical control or adjustment: dependent only upon the forces acting on the rubber and the stiffness of the rubber. The rubber tip would fair downstream: while the force normal to its surface might be smaller than if the surface had not bent, the athwartship component of this normal force, i.e., the lift, would be larger than if acting on a straight surface. By similar reasoning, it was believed that the longitudinal component of the force, i.e., the drag, would be less.

It was decided to experiment on a comparative basis, using one all metal rudder as the basis of comparison; a parent rudder, so to speak. Then five more rudders would be made from the same mold as the parent rudder but with 10%, 20%, 30%, 40%, and 50% of the rudder surface replaced with rubber. The rubber of all rudders was to be cut from the same sheet, to insure that the same rubber characteristics were present

on all rubber-tipped rudders.

An order for the manufacture of the six rudders was placed with the Boston Naval Shipyard and in due time all six rudders were manufactured. The metal portion was "Composition G Bronze" and the rubber was cut from a sheet of gasket material and cemented to the metal with deck tread cement. While the job order called for a rubber percentage of 10%, 20%, 30%, 40%, and 50%, it was found upon careful measurement that, due to manufacturing errors, the actual percentages of exposed rubber, as measured along the side of the rudders, were as follows:

ORDERED	RECEIVED
0%	0%
10%	15.4%
20%	25.0%
30%	33.9%
40%	40.7%
50%	48.7%

Throughout this thesis the rudders are referred to as 10%, 20%, 30%, 40%, and 50% rubber. It should be borne in mind that the actual percentages are as listed above, under the RECEIVED column.

The actual rudder dimensions are as shown in Figure XI.

Due to the necessity of hand finishing the rubber portion of the rudders, there were slight differences found between rudders, but not of such an extent as to invalidate the comparative results obtained from the experiments. It is worthy of note, however, that due to the construction of the joint between the metal and the rubber, a continuous smooth surface for presentation to the flow of water was not attained, with possible attendant effect on drag components.

The forces acting on the rudder were to be measured by the dynamometer developed and built by Kissinger & Rupp, and described in Appendix A.

The rubber swim fins used by swimmers in gaining ahead thrust, and the shape of racing shell oars used to gain "negative drag" were factors given consideration in the development of the idea of semi-flexible rudders. This same idea was also strengthened by some of the facts found in Nature, such as the extreme mobility of fish tails and the softer feather tips in the trailing edge of birds' wings.

III. PROCEDURE

The first step to be accomplished in the experimental work was accurate calibration of the rudder dynamometer. This was performed by placing the dynamometer in a test rack outside the tunnel and by applying known forces to the rudder stock in a direction which would be parallel to the flow of water, with the dynamometer in the tunnel, and in a direction perpendicular thereto. Calibration curves were then prepared as in Figure XII. With the rudder in the tunnel, strain gage readings of deflections in micro-inches were then easily converted to pounds force.

Water speed to be used throughout the experiment was set at 9 ft/sec. in order to stay well within the forces used in the calibration of the dynamometer. During the running of the tests, the water speed was kept under constant monitoring to insure that it was maintained at exactly 9 ft/sec., which corresponds to a Reynolds number of 371,600 (for fresh water at 60°F).

Due to the construction of the dynamometer, the range of rudder angle that could be applied was from 10 degrees left rudder to 36 degrees right rudder.

A "run" consisted of measuring lift and drag forces every few degrees: 3, 5, 7, 10, 13, 15, 17, etc., over the full range of the dynamometer. The location of "zero rudder" was determined by the point at which the Lift Force curve of the run being made crossed the zero axis, going from positive to negative. The Lift and Drag Forces were converted

III. [illegible]

[illegible]

to dimensionless coefficients as defined in hydromechanics literature:

$$C_L = \frac{F_L}{1/2\ \rho\ s\ V^2} \qquad C_D = \frac{F_D}{1/2\ \rho\ s\ V^2}$$

Three complete runs for all rudders were made, with three additional runs made on the parent all metal rudder in order to insure that the basis for comparison of the remaining family of rudders was sound and accurate. Numerous checks of various points on the Lift and Drag curves were made to insure that consistent results were being obtained.

The calibration of the dynamometer was checked repeatedly during the course of the experimental work.

Upon the completion of the experimental work, the results were plotted in the form of curves of rudder angle vs. Lift and Drag Coefficients for all six rudders and of the following cross curves:

Lift Coefficient vs. Percent Rubber

Drag coefficient vs. Percent Rubber

Lift Coefficient/Drag Coefficient vs. Rudder Angle

IV. RESULTS

The results of the experimental work involved in this thesis are shown in the curves on Figures I to X, inclusive. The only variable quantities entering into the results are the percentage of rubber on each rudder and the water density. The water density was corrected for temperature throughout. The velocity of the water was kept constant at 9 ft/sec. The area of all rudders is taken as 36 square inches, i.e., projected area (12).

Observation of the experimental runs in progress showed that the rubber did not flex nearly as much as was anticipated, indicating that the rubber used was too stiff. With 50% rubber a slight but definite deflection was noticed.

A galvanometer was used to indicate balance in the SR-4 Strain Gage Indicator, in measuring forces on the rudder. It was anticipated that with the rubber tips on the rudders there would be a considerable amount of flutter or vibration, which would show on the galvanometer, probably making it difficult to balance. This, however, was not the case. In measuring lift, the amount of vibration appeared to be about the same for both the solid and rubber-tipped rudders. In measuring drag, it was found that the rubber-tipped rudders gave remarkably more steady readings than were given by the all metal rudder.

Figures I to VI are individual plots for each rudder. Figures VII to X give comparative results among the rudders in the form of cross-curves and multiple plots.

IV. RESULTS

The results of the experiment were [illegible] to fully verify the given in the curves on Figures 1 to 4, inclusive. The only notable exception occurred when the results are the [illegible] of rubber on sand, rubber and the water density". The water density was [illegible] for [illegible] the velocity of the water was also [illegible] at 3 ft/sec. The area of the radiator is taken as 24 square inches, i.e., [illegible] area [illegible].

Observation of the experimental runs in progress showed that the rubber did not flow nearly as much as was anticipated, indicating that the rubber used was too stiff. It is felt that a slightly less durometer rubber was [illegible].

A galvanometer was used to indicate balance in the [illegible] Under balance, no measuring device as [illegible]. It was originally felt that the rubber tips on the radiator inlets would be a considerable element of friction or vibration, which would show on the galvanometer, possibly causing it difficult to balance. This, however, was not the case. In connecting the [illegible] the element of vibration appeared to be about the same for both the rubber-tipped radiators. In connecting wires, it was found that the slipped insulation gave considerably [illegible] than were given by the all metal radiator.

FIGURE I

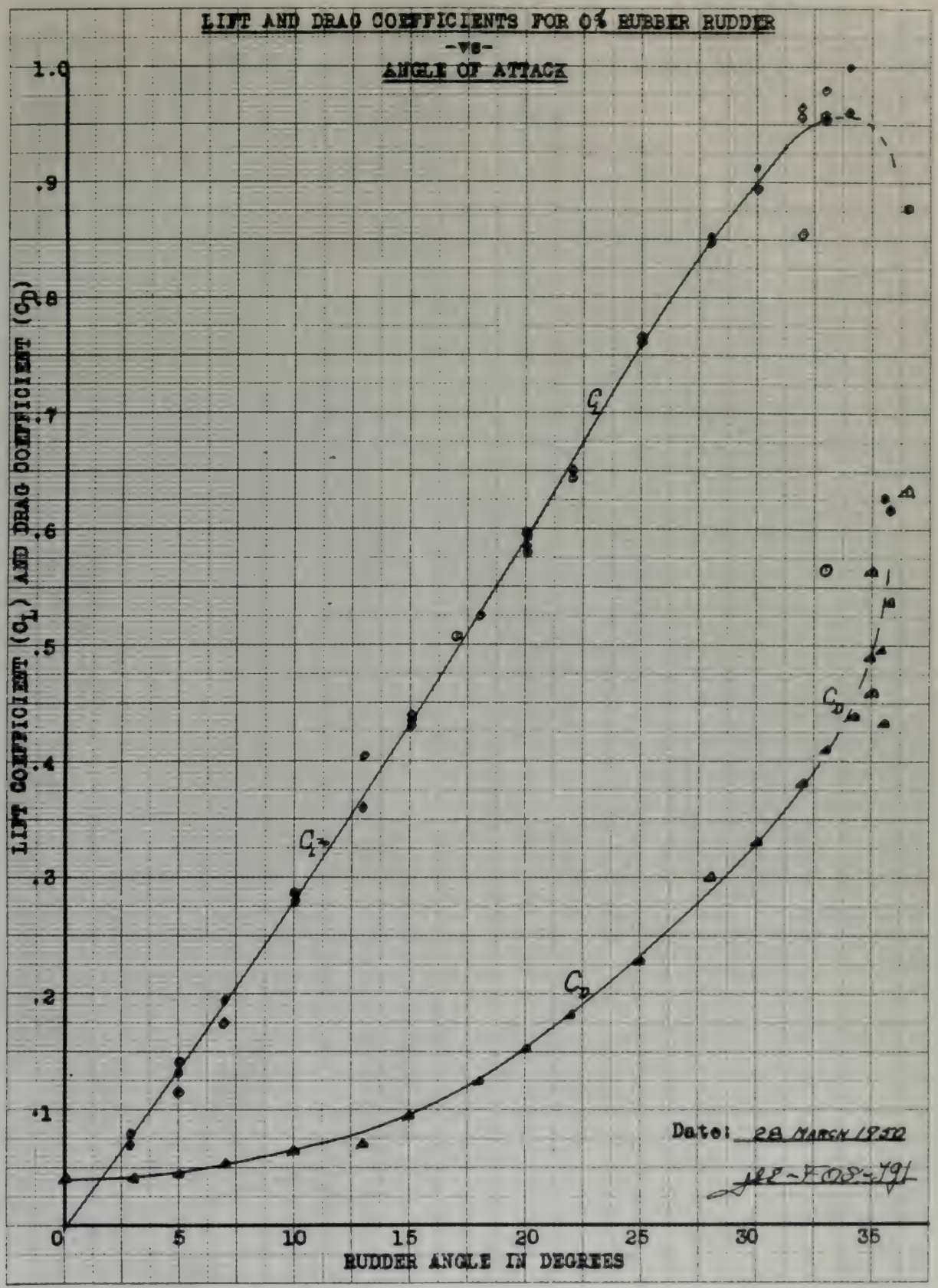

LIFT AND DRAG COEFFICIENTS FOR 0% RUBBER RUDDER
-VS-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
C_L
C_D
C_D
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
Date: 28 MARCH 1950
AE-F-08-791

FIGURE II

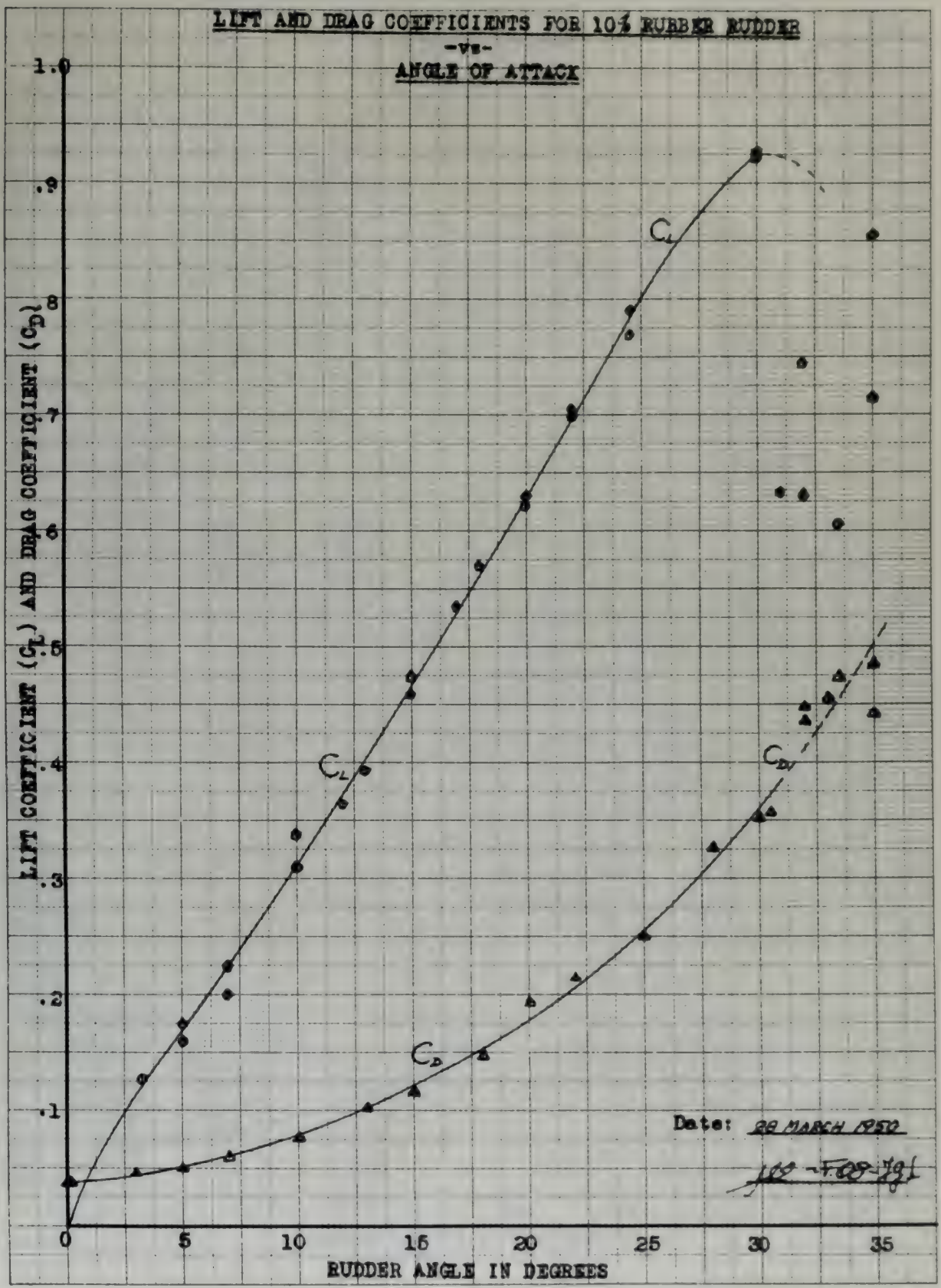

LIFT AND DRAG COEFFICIENTS FOR 10% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
C_L
C_L
$C_{D'}$
C_D
Date: 28 MARCH 1950
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES

FIGURE III

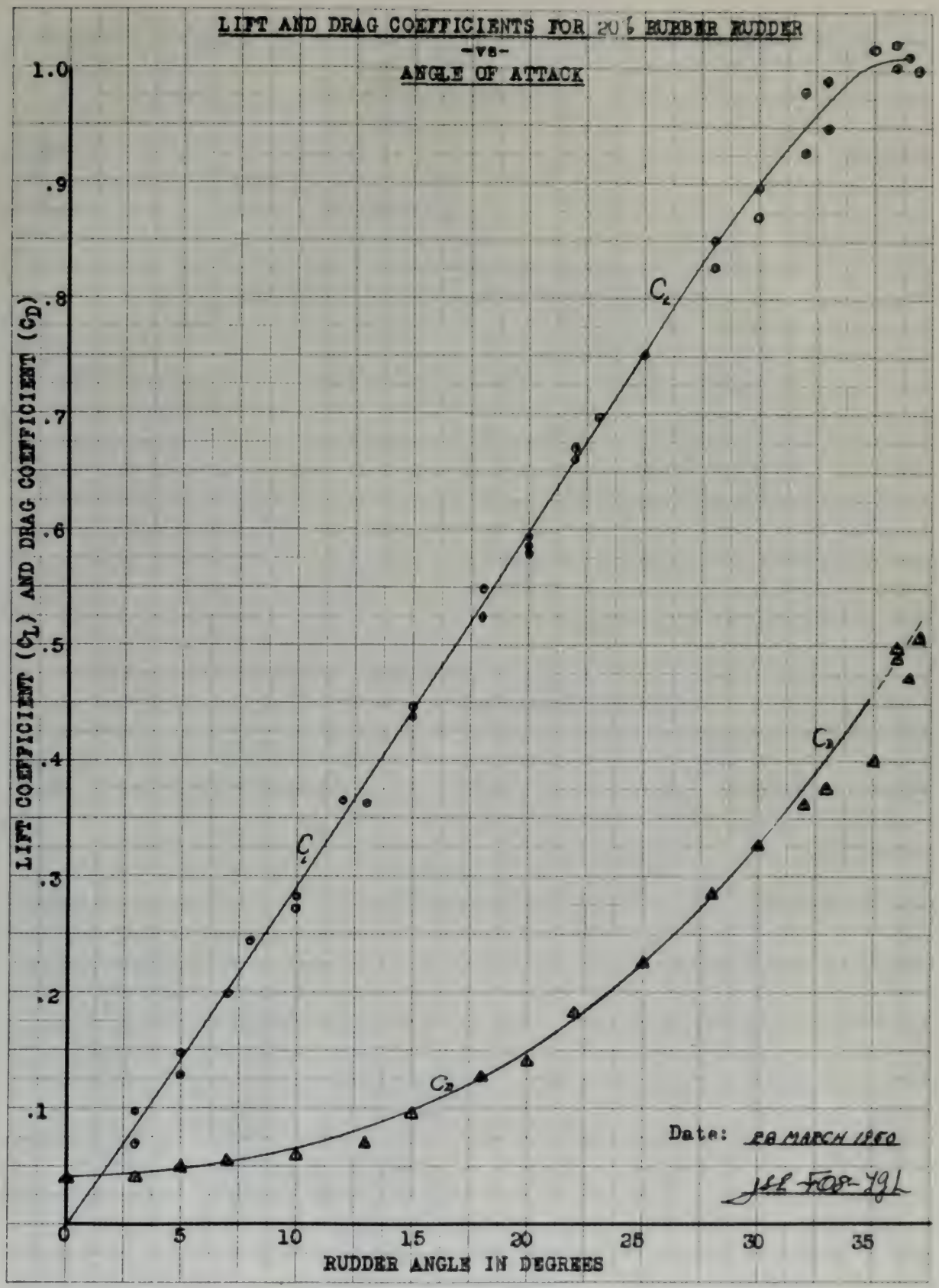

LIFT AND DRAG COEFFICIENTS FOR 20% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
C_L
C_1
C_2
C_3
Date: 28 MARCH 1950
JEE FOR-791

FIGURE IV

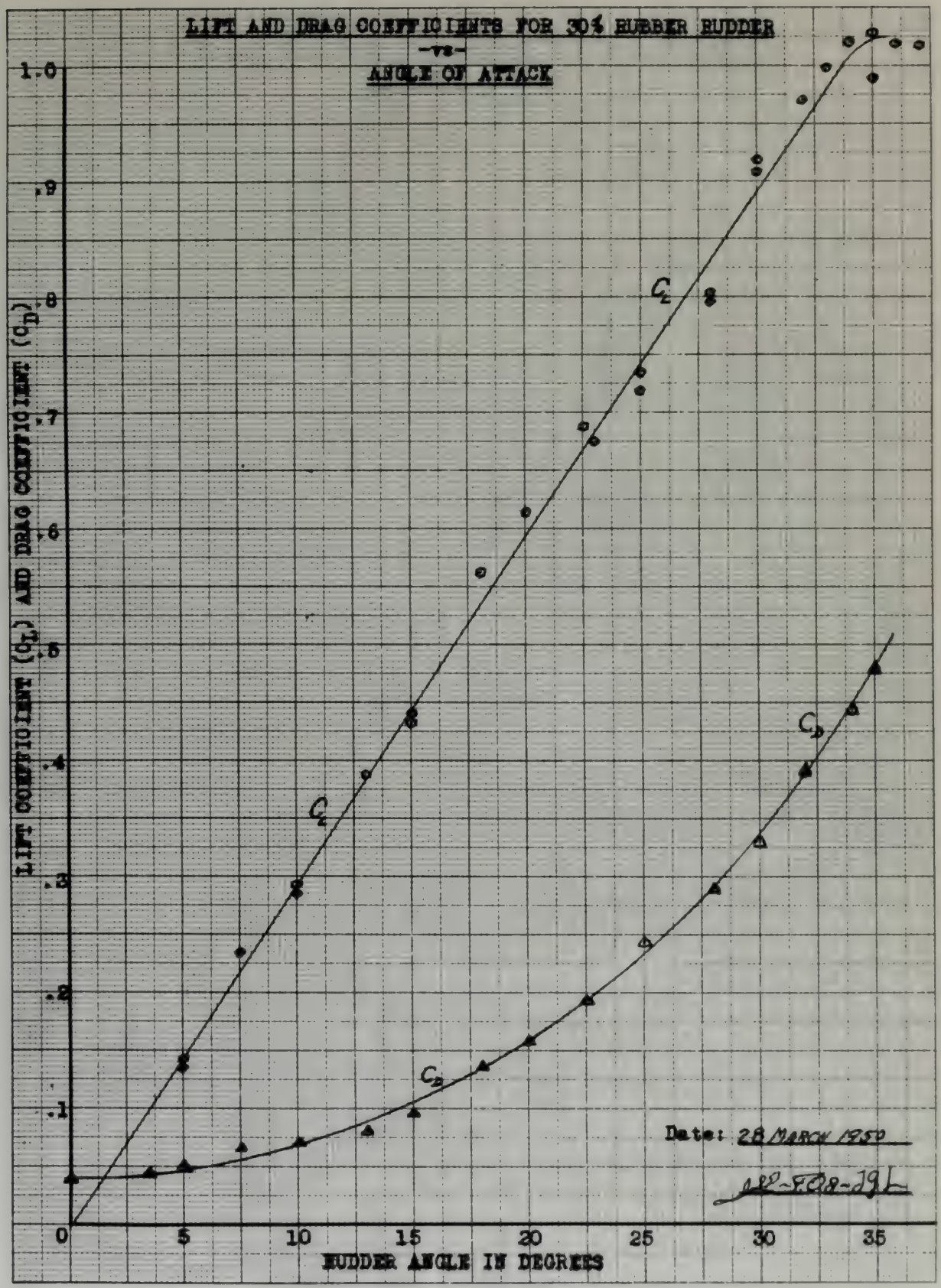

LIFT AND DRAG COEFFICIENTS FOR 30% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
C_L
C_D
C_L
Date: 28 MARCH 1950
NP-FOR-19L

FIGURE V

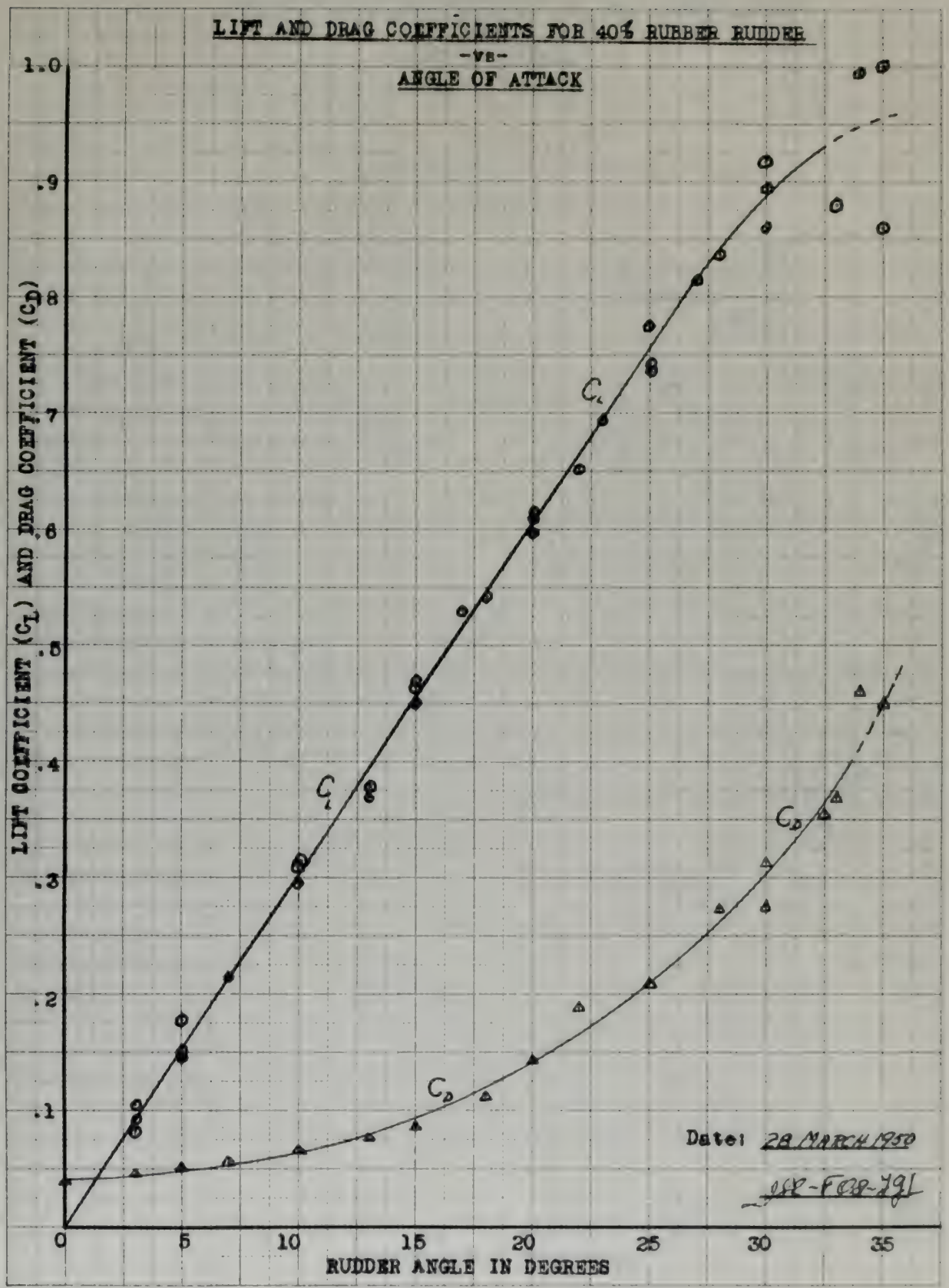

LIFT AND DRAG COEFFICIENTS FOR 40% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
C_L
C_L
C_D
C_D
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
Date: 28 MARCH 1950
NACA-FOR-791

FIGURE VI

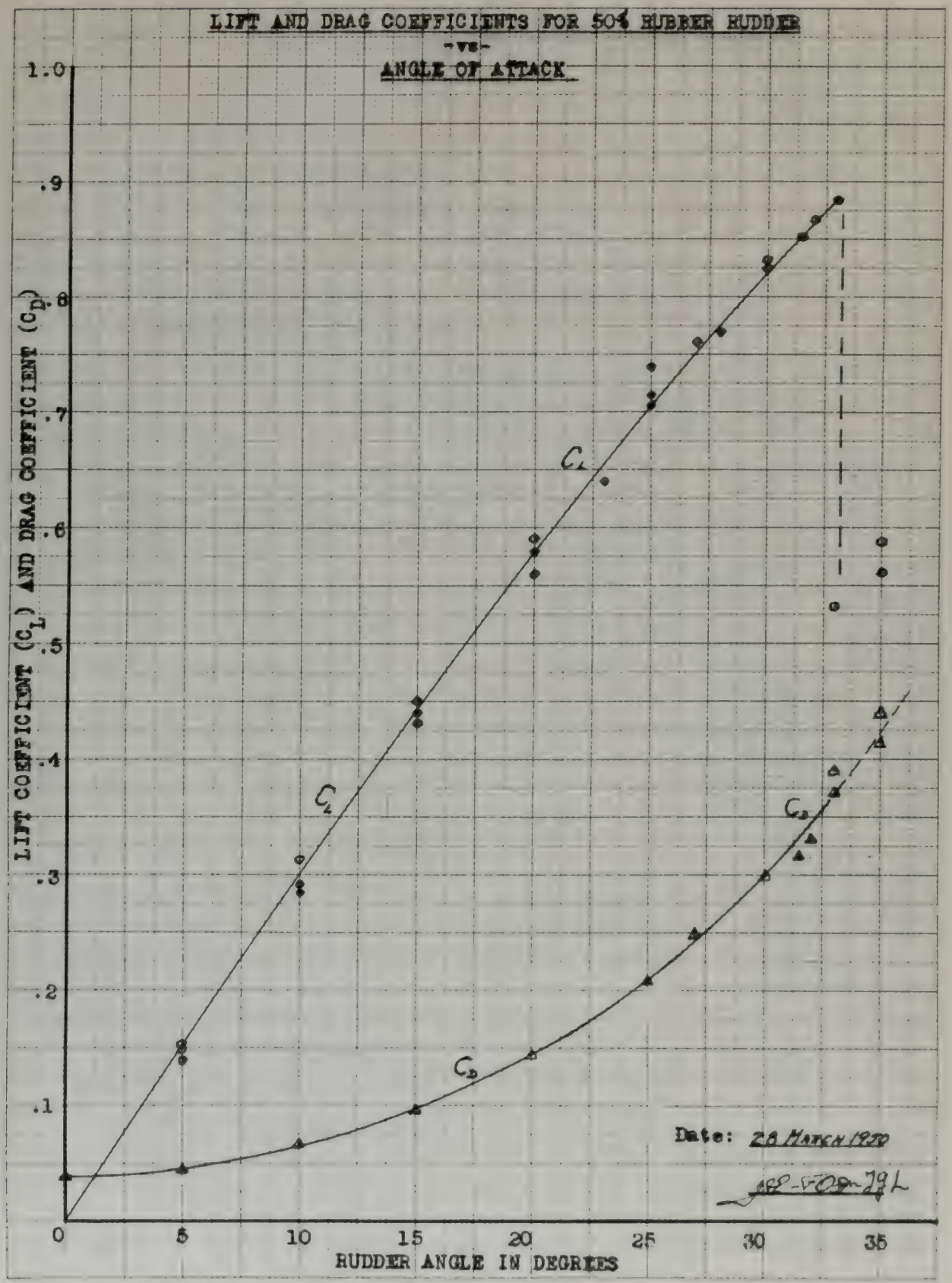

LIFT AND DRAG COEFFICIENTS FOR 50% RUBBER RUDDER
-vs-
ANGLE OF ATTACK
LIFT COEFFICIENT (C_L) AND DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES
C_L
C_L
C_D
Date: 28 March 1930
AER-5-FOR-29L

FIGURE VII

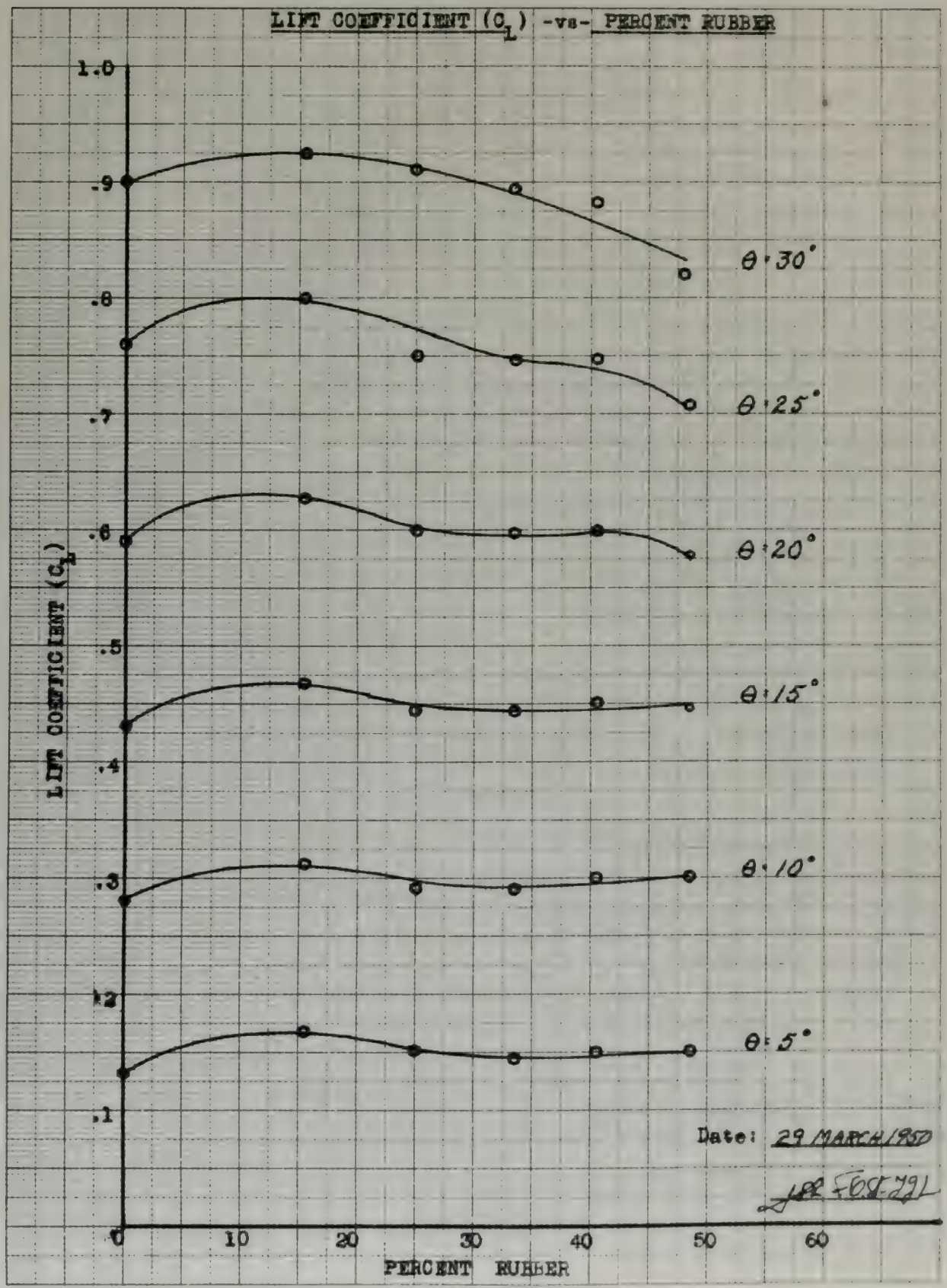
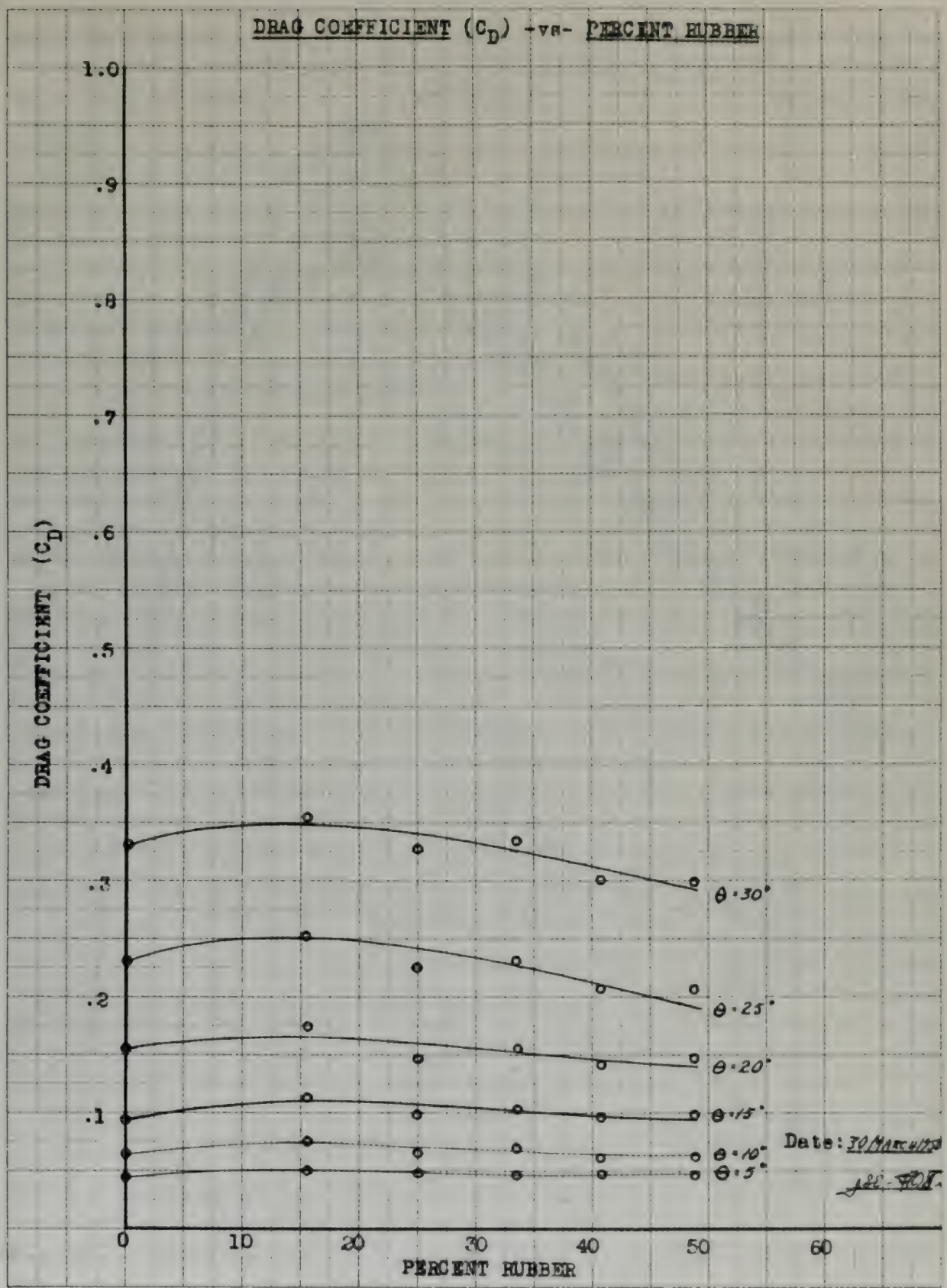

LIFT COEFFICIENT (C_L) -vs- PERCENT RUBBER
LIFT COEFFICIENT (C_L)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
θ=30°
θ=25°
θ=20°
θ=15°
θ=10°
θ=5°
Date: 29 MARCH 1950
0
10
20
30
40
50
60
PERCENT RUBBER

FIGURE VIII


DRAG COEFFICIENT (C_D) -vs- PERCENT RUBBER
DRAG COEFFICIENT (C_D)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
10
20
30
40
50
60
PERCENT RUBBER
θ·30°
θ·25°
θ·20°
θ·15°
θ·10°
θ·5°
Date: 30 March 1

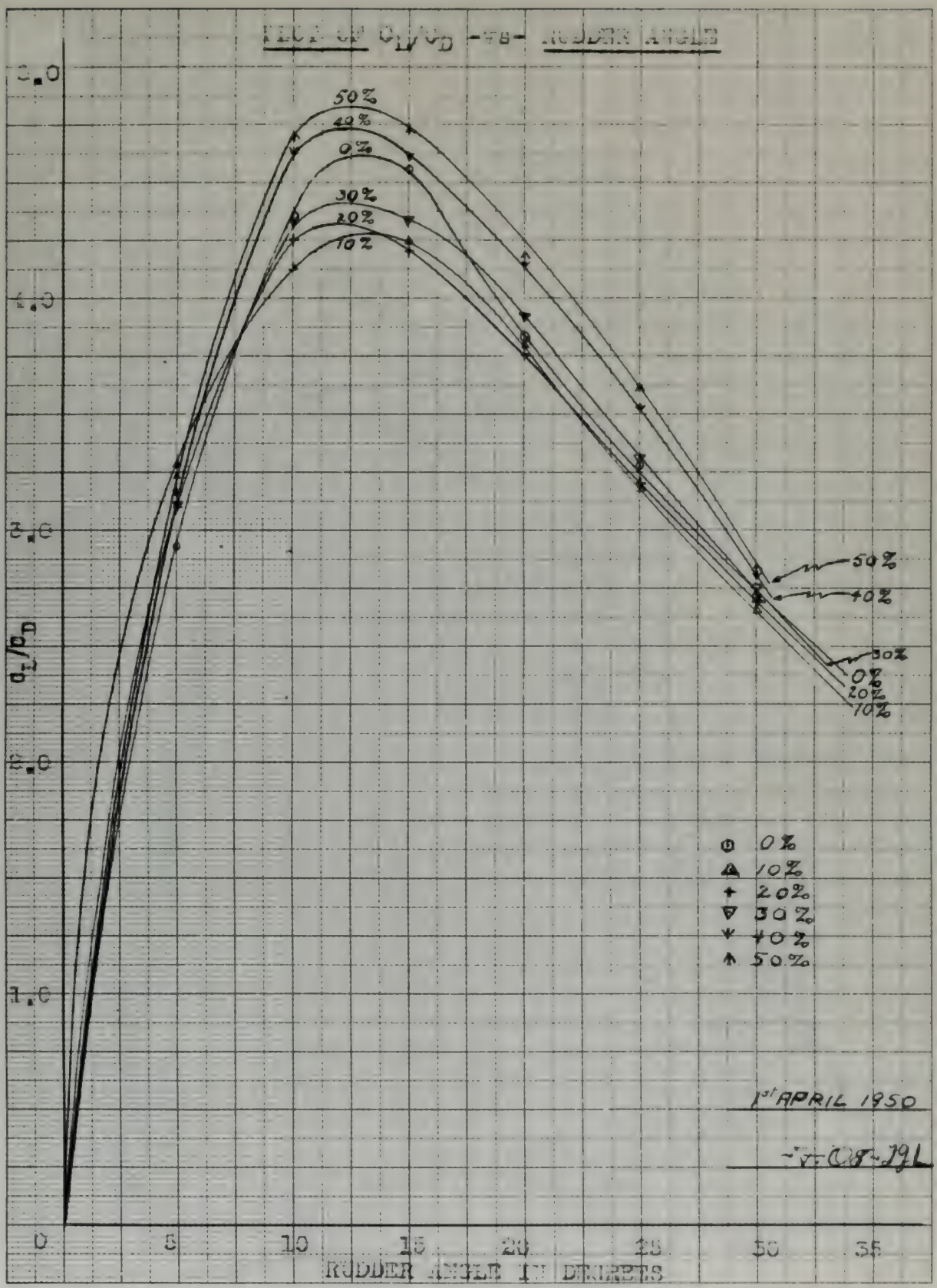
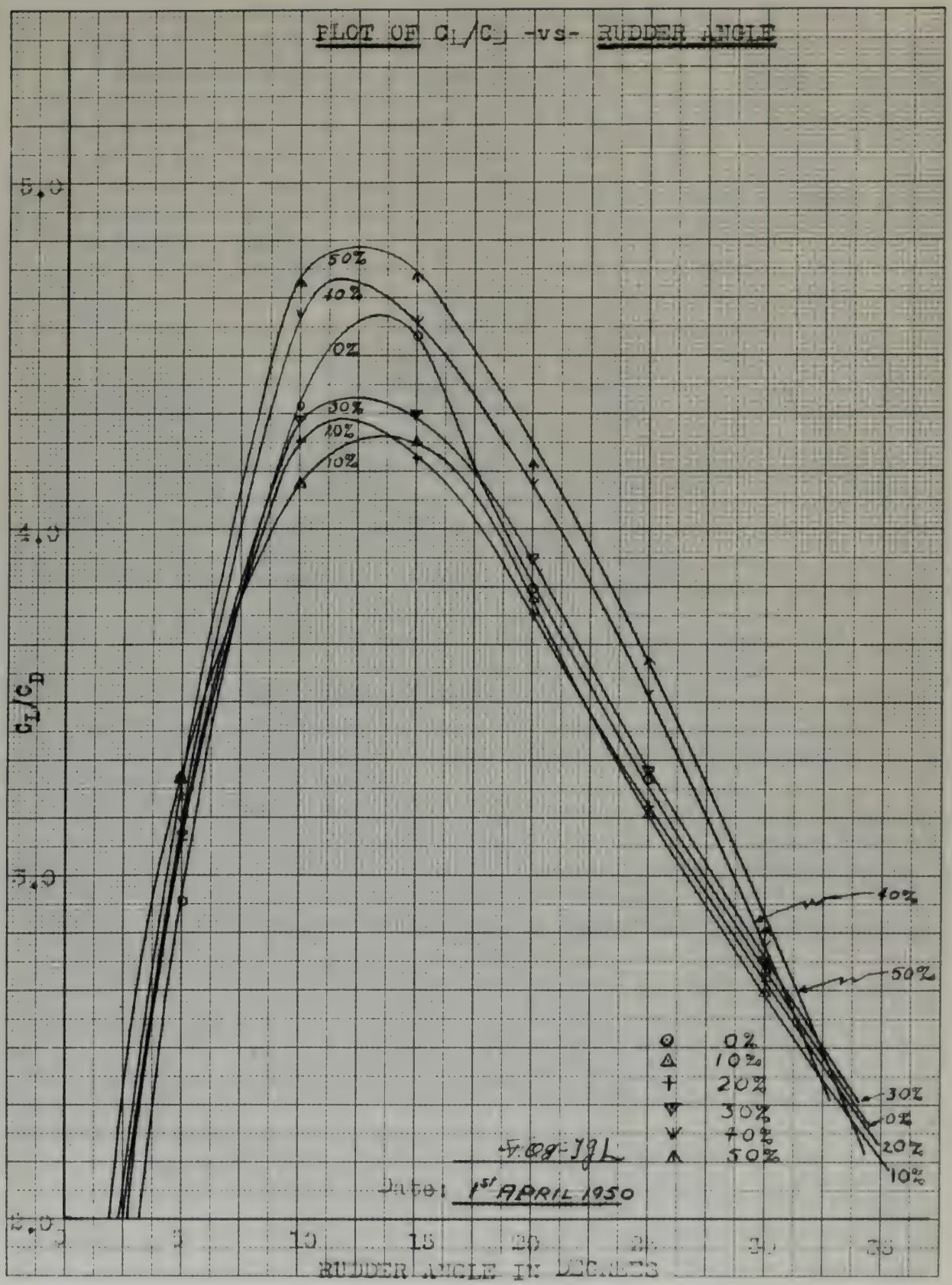

VALUE OF C_L/C_D -VS- RUDDER ANGLE
5.0
4.0
3.0
2.0
1.0
C_L/C_D
50%
40%
0%
30%
20%
10%
0%
10%
20%
30%
40%
50%
1st APRIL 1950
V-08-19L
0
5
10
15
20
25
30
35
RUDDER ANGLE IN DEGREES

FIGURE X


PLOT OF C_L/C_D -vs- RUDDER ANGLE
C_L/C_D
RUDDER ANGLE IN DEGREES
50%
40%
0%
30%
10%
10%
10%
50%
0% 30%
10% 0%
20% 20%
30% 10%
40%
50%
F.O.G. JGL
Date: 1st APRIL 1950

V. DISCUSSION OF RESULTS

The intention of the experiment was to determine the characteristics of rudders with 10%, 20%, 30%, 40%, and 50% rubber. However, the rudders as received from the Boston Naval Shipyard and as tested, had the following percentages of rubber:

15.4%	in	lieu	of	10%
25.0%	"	"	"	20%
33.5%	"	"	"	30%
40.7%	"	"	"	40%
48.7%	"	"	"	50%

There are several possible sources of error in the experimental results obtained which it is well to recognize at this time. First, while the rubber tips used on all rudders were cut from the same sheet of rubber, in an attempt to have rubber with the same characteristics on all rudders, the necessary fitting and machining of the rubber in the process of manufacturing the finished product did introduce some small differences among rubber tips. Secondly, the method of attachment of the rubber to the metal was of such a nature that the drag coefficient might be increased due to the break at the juncture (see the 50% rubber rudder of Figure 18). Thirdly, the rubber tip on the 10% rudder seems to be of a rougher surface than any of the other rubber tips, all of which had the same feel to the hand. This slightly rougher rubber surface, on the 10% rudder, may account in part for the increased drag observed with this rudder.

The rudders were balanced about the rudder stock by drilling out metal aft of the stock until a hanging balance was obtained. These holes were closed with putty prior to running tests in the tunnel, hence insuring

5. DEFINITION OF TERMS

The intention of the experiment was to determine the characteristics of rubbers with 15%, 10%, 30%, 40%, and 45% rubber. However, the rubbers as received from the Akron Rural Shippers and as tested, had the following percentages of rubber:

15.4% to like of 15%
19.8% " " " 20%
31.2% " " " 30%
40.7% " " " 40%
44.7% " " " 45%

There are several possible sources of error in the experimental results obtained which it is well to recognize in this study. First, while the rubber tips used on all rubbers were cut from the same sheet of rubber, in an attempt to have rubber with the same characteristics on all rubbers, the necessary fitting and moulding of the rubber in the process of mounting the finished product may introduce some small difference among rubber tips. Secondly, the removal of elongation of the rubber in the round was of such a nature that the drag coefficient might be increased due to the irregularities at the junctures (see the 30% rubber rubber of figure 15). Thirdly, the rubber tip on the 15% rubber seemed to be of a rougher surface than any of the other rubber tips, all of which had the same load to the bend. This slightly rougher rubber surface, on the 15% rubber, may account in part for the increased drag observed with this rubber.

The rubbers were balanced about the rubber stems by drilling out metal at the stem until a bending balance was obtained. These holes were closed with putty prior to painting them in the tunnel. Hence inserting

a smooth surface.

The metal portion of all rudders should be very nearly identical, as all were cast to the same mold. No discrepancies among the metal portions of the family of rudders was discernible.

No sources of error, other than the ever present human element, are known at this time, to exist.

From a study of figures I and VI, and observation of the tests as they were conducted, rudder breakdown seems to occur as follows:

RUDDER	RUDDER ANGLE AT BREAKDOWN
0%	30°
10%	30°
20%	32°
30%	35°
40%	32°
50%	33°

From these figures it would appear that the addition of rubber does not hasten the arrival at the breakdown angle and does have the effect of delaying this angle a few degrees.

Figure VII shows that Lift is increased by the use of rubber up to about 25% rubber at all angles of attack, but that with more than 25% of rubber the Lift falls off at angles of attack above 15°.

From Figure VIII it is seen that Drag increases with the use of rubber up to about 25% rubber and that with more than 25% rubber, the Drag decreases.

In Figures I-VI the location of 0° angle of attack was determined by measuring Lift from right rudder to left rudder and plotting the Lift against the angle of attack as indicated on the dynamometer movable head. This

a smooth surface.

The normal position of all vanes should be very nearly horizontal, as all were cast in the same mold. No discrepancies among the normal positions of the family of vanes was discovered.

The success of wings, other than the ever present human element, are known at this time, to exist.

From a study of figures 1 and VI, and observation of the tests as they were conducted, vaious investigations appear to occur as follows:

ANGLE	ATTACK AT WHICH OCCURS
5°	30°
10°	25°
15°	20°
20°	14°
40°	12°
50°	12°

From these figures it would appear that the addition of another plane set between the vertical at the forward angle and those more for object of decreasing this angle a few degrees.

Figure VII shows that Lift is increased by the use of ailerons up to about 12° rather at all angles of attack, but what would appear that 12° of rudder the Lift falls off at angles of attack above 12°.

From Figure VIII it is seen that Drag increases with the use of rudder up to about 12° rudder and that was, more than 12° rudder, the Drag decreases.

In Figure 1-VI the location of C angle of attack was determined by measuring L.E from right vertical to left rudder and plotting on L.E again the angle of attack as indicated on the aforementioned lines. This

plot was very nearly a straight line and 0° angle of attack was set at the point where the plotted line crossed (zero lift) the coordinate axis showing rudder angle in degrees.

In order to produce comparative results, the drag for zero angle of attack for all rudders was corrected to the drag of the all metal rudder at zero angle of attack. For each rudder, this very small correction was applied to all values of the Drag Coefficient, thence the curves were plotted.

Beyond the point at which the rudder was believed to have reached breakdown, the Coefficient curves are dotted in, as the exact behavior of the rudder beyond this point was indeterminate.

The model Rudder Dynamometer would not give readings above 36 degrees right rudder and 10 degrees left rudder.

VI. CONCLUSIONS

1. With respect to the all metal rudder, the use of rubber in the construction of the rudders increased the Lift Coefficient, the maximum increase being obtained with about 12 1/2% rubber. Beyond about 25% rubber the Lift Coefficient decreases.
2. The Drag Coefficient increases up to about 25% rubber, decreasing with increase of rubber beyond 25%.
3. With respect to the all metal rudder the C_L/C_D ratio is larger for all rubber-tipped rudders at small angles of attack, below about 8°. This ratio is larger for the 40% rubber rudder at all angles of attack.
4. The rubber used in the experiment was too stiff for best performance.

1. [illegible] to the all normal rubber, the use of rubber in the machine-
   [illegible] of the rubber increased for [illegible], the maximum increase
   being obtained with about 10 to 15% rubber. Normal wear is the
   same for [illegible] decreases.

2. The Long Condition Increases as is about 10% natural rubber, [illegible]
   increase of rubber beyond 15%.

3. This request to the all normal rubber the Cr/Cr ratio is larger for all
   rubber-filled [illegible] small angles of attack, below about 5°. This
   ratio is larger for the 85% rubber [illegible] at all angles of attack.

4. The rubber used in the experiments was the [illegible] in some [illegible]

VII. RECOMMENDATIONS

1. That further experimental work be done with semi-flexible rubbers along the following lines:

    a) Utilize rubber of varying degrees of stiffness.

    b) Conduct a close search of the area within the 5% to 15% rubber zone.

    c) Conduct experiments with all rubber rudders in which the forward portion (percentage determined by previous work), of the rudder is stiffened by internal framework so that it is inflexible and the after portion free to flex. Use of such a rudder would exclude the possibility of erroneous results such as increased drag due to the break at the junction of the rubber and metal.

2. That the possibility of using a flexible trailing edge on propellors be investigated.

3. That the effects of the ship's hull and the propellers race on the rubber-tipped rudders be investigated.

VII. RECOMMENDATIONS

1. Tire burber experimental work be done with wear-flexible rubbers along the following lines:

a) Initial content of varying degrees of unsaturation.

b) Elongation values exceeding 400 to 450 in [illegible] rubber zones.

c) Combined experiments with all rubber rubbers to obtain the largest working (processing-determined by practical work), at the rubber is exhibited in tensile [illegible] as close to it [illegible] with the other [illegible]. Use of such a rubber would maximize the possibility of successful results [illegible] to improved flex to the break at the junction of the rubber and metal.

2. That the possibility of using a flexible bracing edge be investigated.

3. That the effects of the ship's hull and the propellers [illegible] on the rubber-lined rudders be investigated.

FIGURE XI

MODEL RUDDERS

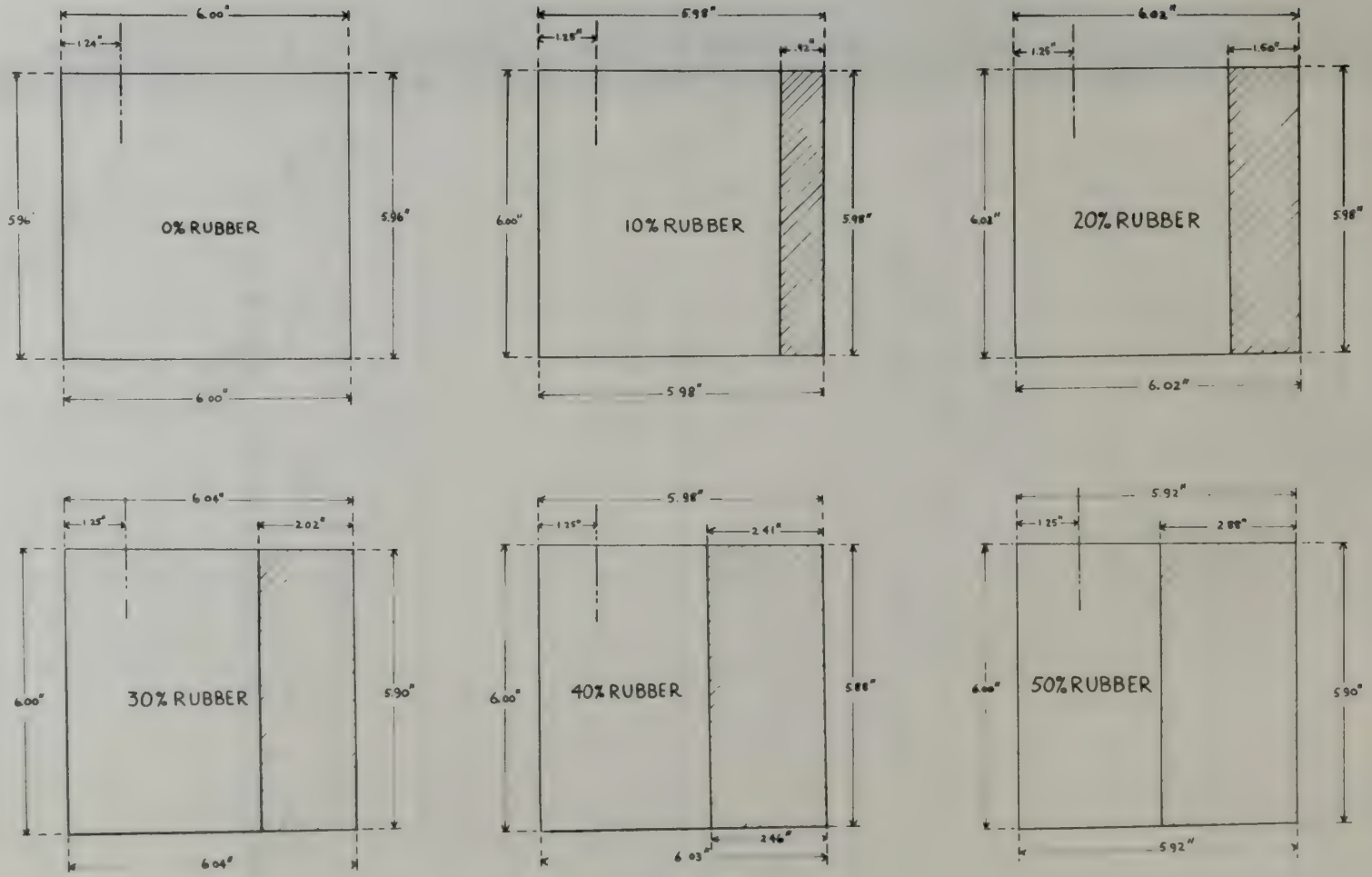


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FIGURE XII

CALIBRATION CURVES FOR RUDDER DYNAMOMETER

APPLIED LOADS VS INSTRUMENT READINGS

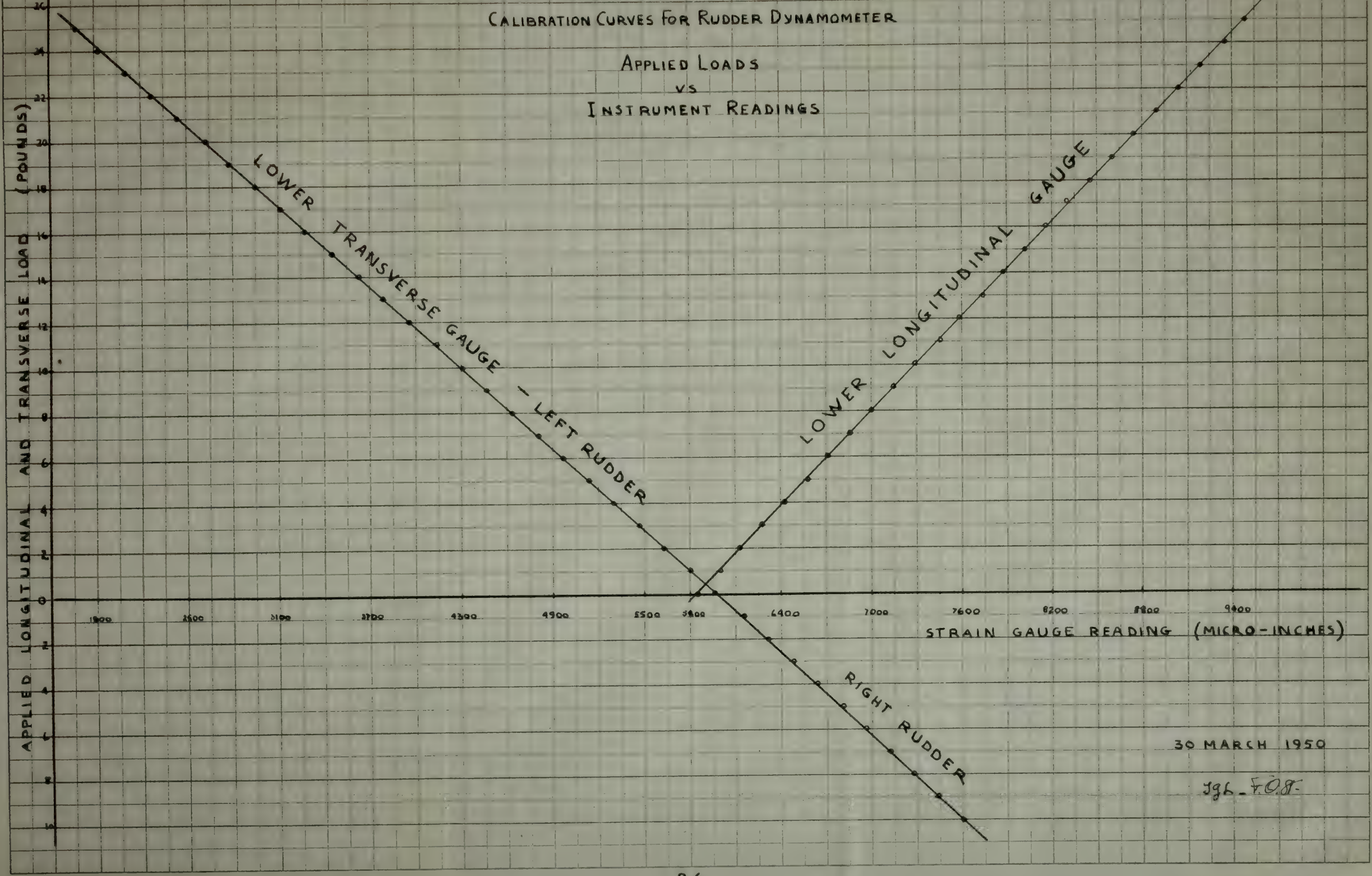

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FIG. XIII - INSTRUMENTS

FIG XIV- INSTRUMENTS AND DYNAMOMETER

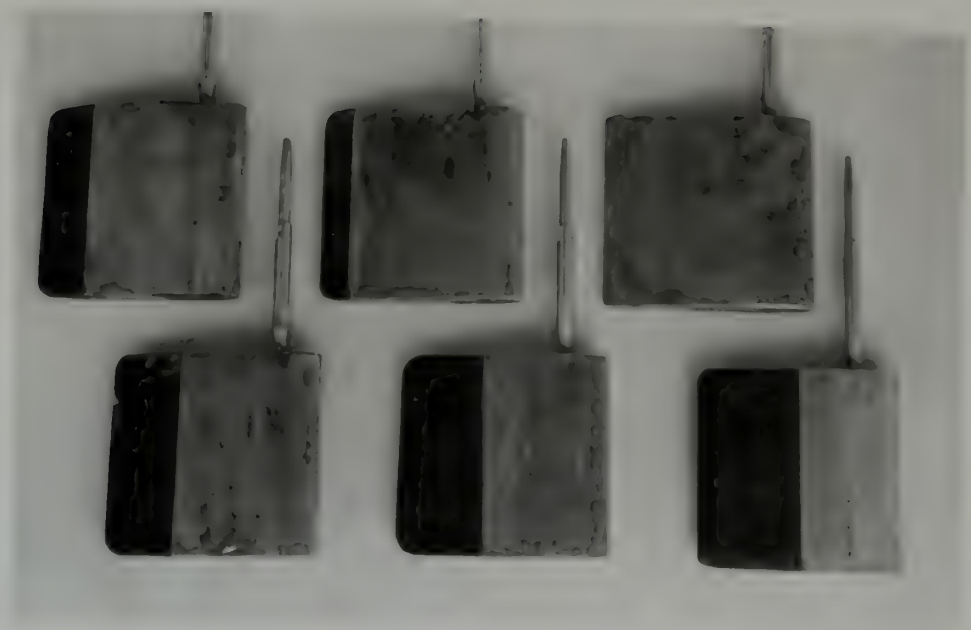


FIG XV — MODEL RUDDERS

FIG XVI – ELEVATION AND PLAN VIEW OF MODEL RUDDERS

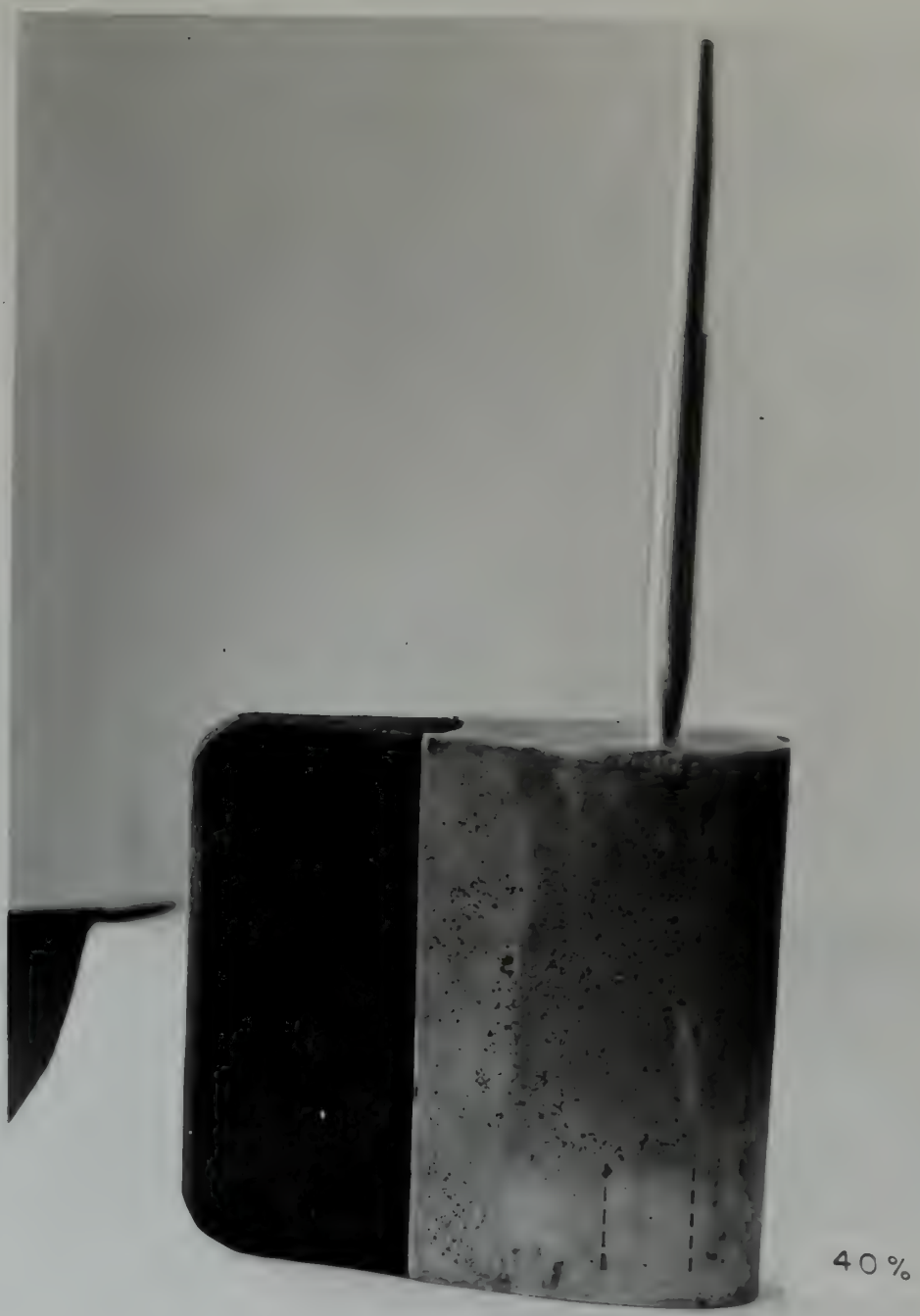


FIG XVII— 40% RUBBER RUDDER

FIG XVIII – RUDDER BEING BENT

FIG XIX – CALIBRATION SET-UP

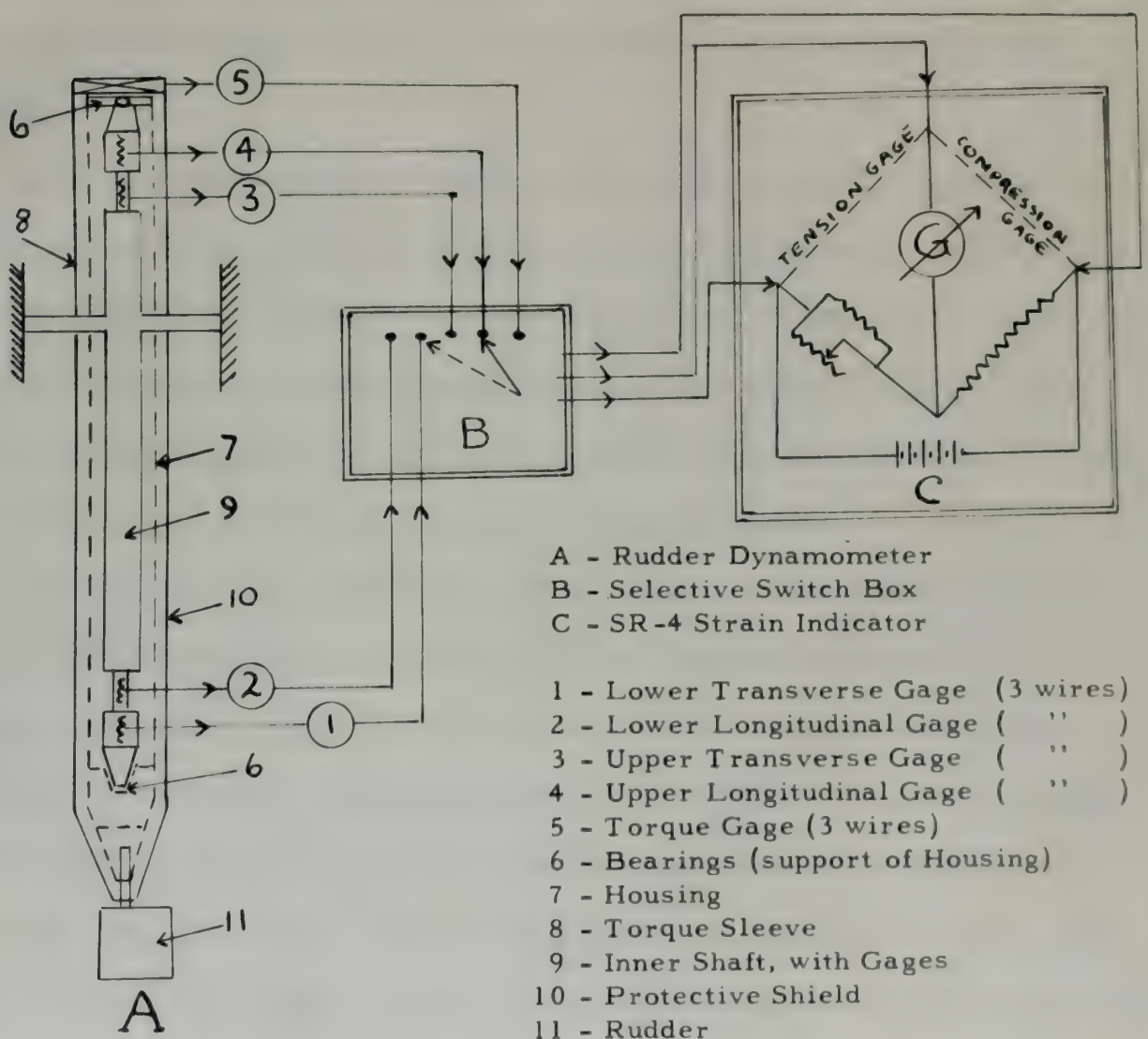
APPENDIX "A"

VIII. APPENDIX

APPENDIX "A"

THE M. I. T. MODEL RUDDER DYNAMOMETER

The measurement of Lift and Drag forces for the development of this thesis was made with the Model Dynamometer designed by Kissinger and Rupp (11). A sketch of the Dynamometer's essential details and a brief explanation of its operation follows:



A - Rudder Dynamometer
B - Selective Switch Box
C - SR-4 Strain Indicator

1 - Lower Transverse Gage (3 wires)
2 - Lower Longitudinal Gage (")
3 - Upper Transverse Gage (")
4 - Upper Longitudinal Gage (")
5 - Torque Gage (3 wires)
6 - Bearings (support of Housing)
7 - Housing
8 - Torque Sleeve
9 - Inner Shaft, with Gages
10 - Protective Shield
11 - Rudder

NOTE: Resistors shown dotted in the Wheatstone Bridge are the pair of gages (tension & compression) in use; they actually are mounted on the dynamometer.

The Model Dynamometer consists of a steel shaft (9) carrying two sets of strain gages (1, 2, 3, 4) and rigidly supported by a casting, which is the only outside support. The four strain gages are mounted in two mutually perpendicular reduced sections at the upper and lower end of the shaft, i.e., parallel and normal to the water flow. The shaft is enclosed by a watertight cylinder (7) which is supported at both ends of the shaft (9). The rudder stock is firmly held by this cylinder, thus transmitting all forces to the inner shaft.

Above the dynamometer support a sleeve (5) is mounted around the cylinder; the torque gage is installed between this sleeve and the cylinder (7). This gage will not be discussed here as it was not used during the experiments.

Below the Dynamometer support there is a protective shield (10) with the lower end tapered. To avoid corrections for drag forces this tapered end was brought very close to the upper surface of the rudder.

The strain gages consist of fine wires cemented to the reduced sections in the direction of the pure bending introduced by either longitudinal or transverse forces. Three electrical leads are used with each strain gage, namely - tension side, compression side and neutral axis (common ground). The leads from all gages were connected to a selective switch box which in turn was connected to the SR-4 Strain Indicator. This indicator consists of a built-in Wheatstone bridge with galvanometer for obtaining balance among the resistances. A high sensitivity, as well as temperature correction, was obtained by connecting simultaneously the tension and compression leads from the gage in use to the SR-4 Indicator.

Due to changes made in the Dynamometer it was decided to use only the two lower strain gages, the location of the upper gages making their readings less sensitive than the lower. During calibration of the Lower Longitudinal Gage, care was taken to insure that only longitudinal forces would act on the Dynamometer (by keeping zero reading on the Transverse Gage). Therefore, the SR-4 Indicator reading for a given longitudinal force was always the same, regardless of the readings of the upper gages. The same applies to the Lower Transverse Gage.

This procedure simplifies the use of the Rudder Dynamometer as it does not require the resolution of the applied load into its upper and lower components, as was required in the original design.

The use of the SR-4 Strain Indicator together with the selective switch simplified considerably the test procedure.

For a detailed explanation of the Rudder Dynamometer the reader is referred to reference (11) in the bibliography.

APPENDIX "B"

CALIBRATION DATA

(Ahead motion) Date: 2/24/1950

Gauge Lower Transverse (LT)		Gauge Lower Longitudinal (LL)	
Applied Load	Strain reading (micro-inches)	Applied Load	Strain reading (micro-inches)
Left rudder		----------	
0#	5960	0#	5850
1	5800	1	6000
2	5630	2	6130
3	5470	3	6280
4	5300	4	6430
5	5140	5	6580
6	4970	6	6715
7	4810	7	6860
8	4640	8	7000
9	4470	9	7145
10	4310	10	7290
11	4140	11	7430
12	3960	12	7585
13	3790	13	7740
14	3630	14	7875
15	3460	15	8020
16	3280	16	8160
17	3115	17	8300
18	2950	18	8450
19	2780	19	8600
20	2620	20	8745
21	2430	21	8900
22	2270	22	9045
23	2100	23	9190
24	1930	24	9340
25	1780	25	9490
		26	9630
Right Rudder			
1	6150		
2	6310		
3	6480		
4	6640		
5	6810		
6	6960		
7	7120		
8	7280		
9	7440		
10	7610		

	Left rudder		
0#	5960	0#	5950
1	5800	1	6000
2	5630	2	6130
3	5470	3	6280
4	5300	4	6430
5	5140	5	6580
6	4970	6	6715
7	4810	7	6870
8	4640	8	7020
9	4470	9	7145
10	4310	10	7290
11	4140	11	7430
12	3960	12	7585
13	3790	13	7740
14	3630	14	7875
15	3460	15	8020
16	3280	16	8160
17	3115	17	8300
18	2950	18	8450
19	2780	19	8600
20	2620	20	8745
21	2430	21	8900
22	2270	22	9045
23	2100	23	9190
24	1950	24	9340
25	1780	25	9490
		26	9630

	High Rudder
1	6130
2	6280
3	6440
4	6590
5	6740
6	6890
7	7040
8	7190
9	7340
10	7490

The calibration curves (Figure XII) were plotted after obtaining the data from the preceding page and were used throughout the tests, checks being made after each series of runs.

SAMPLE LIFT COEFFICIENTS USED ON PLOTS*

Rudder Angle	Rudder 0%	Rudder 10%	Rudder 20%	Rudder 30%	Rudder 40%	Rudder 50%
0°	0.0	0.0	0.0	0.0	0.0	0.0
3	.069	.127	.097		.092	
5	.132	.175	.147	.143	.150	.153
7	.175	.225	.200	.234	.215	
10	.279	.309	.283	.292	.310	.313
13	.360	.393	.362	.367	.378	
15	.429	.475	.446	.441	.465	.450
18	.525	.570	.550	.562	.542	
20	.585	.630	.587	.614	.608	.580
22	.644	.705	.671	.688	.654	
25	.760	.790	.752	.735	.743	.715
28	.847		.850	.804	.837	.770
30	.894	.927	.897	.908	.894	.825
32	.955	.630	.980	.970		.868
33	.953	.605	.991	.996	.880	.532
34	.960			1.021	.994	
35		.715	1.018	1.028	.860	.561

* The above tabulation refers to one series of runs only.

The curves of Figures I to VI were plotted with data of five complete series of runs.

SAMPLE DRAG COEFFICIENTS USED ON PLOTS*

Rudder Angle	Rudder 0%	Rudder 10%	Rudder 20%	Rudder 30%	Rudder 40%	Rudder 50%
0°	.040	.040	.040	.040	.040	.040
3	.041	.046	.040	.044	.046	. -
5	.046	.051	.050	.050	.051	.045
7	.056	.061	.055	.066	.056	. -
10	.066	.077	.060	.071	.066	.066
13	.071	.102	.071	.081	.076	. -
15	.097	.117	.096	.096	.087	.096
18	.123	.148	.127	.137	.112	. -
20	.153	.194	.142	.158	.143	.142
22	.184	.214	.183	.192	.188	. -
25	.230	.250	.224	.244	.209	.209
28	.301	.327	.285	.290	.273	. -
30	.332	.352	.326	.331	.313	.300
32	.383	.357	.362	.392	.355	.331
33	.408	.455	.377	. -	.369	.392
34	.440	. -	. -	.444	.461	. -
35	.460	.485	.400	.479	.450	.439

(*) The above tabulation refers to one series of runs only; the data was corrected for drag at zero rudder angle to be equal for all rudders.

The curves (Figures I to VI) were plotted with data of five complete series of runs.

0°	.000	.000	.000	.000	.000
3	.041	.040	.040	.040	.040
5	.068	.067	.067	.067	.067
7	.095	.094	.093	.093	.093
10	.136	.134	.133	.133	.133
13	.177	.174	.173	.173	.173
15	.204	.201	.200	.200	.200
18	.245	.241	.240	.240	.240
20	.272	.268	.267	.267	.267
22	.299	.295	.294	.294	.294
25	.340	.335	.334	.334	.334
28	.381	.375	.374	.374	.374
30	.408	.402	.401	.401	.401
32	.435	.429	.428	.428	.428
35	.476	.469	.468	.468	.468
37	.503	.496	.495	.495	.495
40	.544	.536	.535	.535	.535

(*) The above tabulation refers to one surface of rough moist ice whose
coverage by dust at zero relative angle is the equal for all radiators.

The curves (figures 1 to 7) were plotted with data of line energies
maxima of rays.

DATA FOR CURVES ON FIGURES IX and X

LIFT COEFFICIENT C_L - vs - RUBBER PERCENTAGE*

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	.132	.167	.152	.146	.148	.162
10°	.283	.310	.298	.293	.295	.302
15°	.433	.467	.450	.445	.445	.450
20°	.593	.628	.602	.595	.599	.580
25°	.760	.797	.775	.748	.739	.701
30°	.898	.925	.915	.890	.865	.833

DRAG COEFFICIENT C_D - vs - RUBBER PERCENTAGE*

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	.045	.051	.049	.047	.047	.047
10°	.065	.075	.070	.068	.064	.064
15°	.095	.110	.107	.103	.097	.095
20°	.155	.165	.160	.152	.145	.138
25°	.232	.251	.242	.226	.210	.193
30°	.330	.348	.340	.325	.310	.292

C_L/C_D - vs - RUBBER PERCENTAGE

ANGLE	PERCENTAGE OF RUBBER					
	0%	10%	20%	30%	40%	50%
5°	2.93	3.28	3.10	3.11	3.15	3.24
10°	4.36	4.13	4.26	4.32	4.62	4.72
15°	4.56	4.25	4.21	4.33	4.59	4.74
20°	3.83	3.80	3.76	3.92	4.13	4.20
25°	3.28	3.18	3.20	3.31	3.52	3.63
30°	2.72	2.66	2.69	2.74	2.79	2.85

*NOTE: These values were taken from faired curves on Figures VII and VIII.

APPENDIX "C"

TYPICAL DATA SHEET

Rudder: 0% rubber

Water temperature: 62°F - Water speed: 9 ft/sec. - Date: 3/24/50

Rudder Angle (right)	Gauge LT Reading	Lift Force	C_L	Gauge LL Reading	Drag Force	C_D
0°	5960	0.0	0.000	5960	0.8	.041
3	5725	1.4	.071	5960	0.8	.041
5	5580	2.3	.117	5970	0.9	.046
7	5380	3.5	.179	5980	1.1	.056
10	5035	5.6	.286	6030	1.3	.066
13	4770	7.1	.362	6050	1.4	.071
15	4530	8.6	.440	6110	1.9	.097
18	4250	10.3	.526	6180	2.4	.123
20	4010	11.7	.596	6260	3.0	.153
22	3750	13.2	.675	6360	3.6	.184
25	3450	15.0	.766	6490	4.5	.230
28	3180	16.6	.848	6670	5.9	.301
30	3030	17.5	.895	6780	6.5	.332
32	2830	18.7	.955	6930	7.5	.383
33	2710	19.4	.990	7000	8.0	.408
34	2650	19.7	1.005	7090	8.6	.440
(left) 5°	6475	3.0	.153	5985	1.0	.051
8	6760	4.8	.245	6020	1.2	.061
10	6960	6.0	.306	6060	1.5	.076

APPENDIX DATA SHEET

[illegible] 45° rotor

Water temperature: 12.2 - Water speed: 3 ft/sec - Time: [illegible]

Rotor Angle (rad)	Change in Reading	Error Band	C_D	Change in Reading	Error Band	C_D
α_n						
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
α_n (rad)						
1						
2						
3						

SAMPLE CALCULATION

From "Sample Data Sheet" on page 45, for 20° right rudder.

Lift Force = 11.7 lbs.

Drag Force = 3.0 lbs.

$$\text{Water density (at } 62^\circ \text{ F)} = \rho = 1.9379 \ \frac{\text{lb.sec}^2}{\text{ft}^4}$$

Rudder area = $S = 0.25 \text{ ft}^2$

Water speed = $V = 9.0$ ft/sec.

$$\text{Lift Coefficient} = C_L = \frac{F_L}{1/2 \rho S V^2} = \frac{11.7}{1/2(1.9379)(0.25)(81)} = 0.596$$

$$\text{Drag Coefficient} = C_D = \frac{F_D}{1/2 \rho S V^2} = \frac{3.0}{1/2(1.9379)(0.25)(81)} = 0.153$$

[illegible]

[illegible] "Example Data Sheet" on page [illegible] for [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

APPENDIX "D"

ORIGINAL DATA

The original data is in the custody of Professor S. Curtiss Powell.

ORIGINAL DATA

The original data is in the custody of Professor S. Curtiss Powell.

APPENDIX "L"

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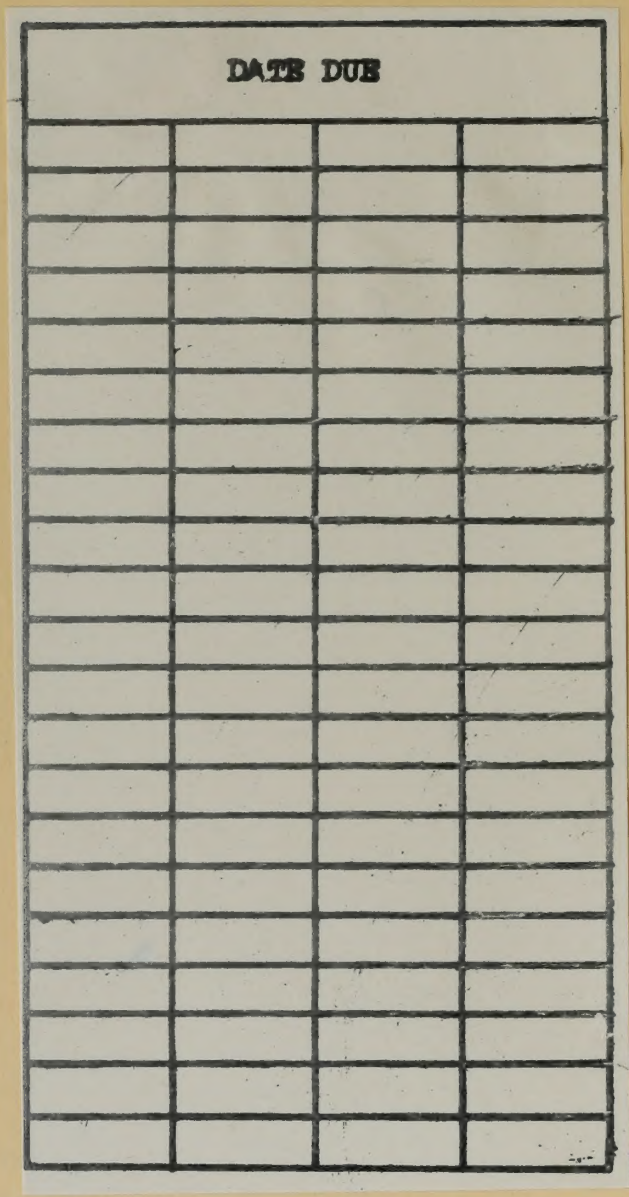
DATE DUE

Thesis 12863
E8 Eversole
Semi-flexible self
varying camber rudder.

Thesis 12863
E8 Eversole
Semi-flexible self
varying camber rudder.

thesE8
Semi-flexible self varying camber rudder
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